INTERPLANETARY METEOROID ENVIRONMENT MODEL UPDATE

Henry B. Garrett†

The Jet Propulsion Laboratory (301-456)

California Institute of Technology

4800 Oak Grove Dr.

Pasadena, CA 91109

S. J. Drouilhet*

Dept. of Mathematics

Moorhead State University

Moorhead, MN 58103

John P. Oliver§

Dept. of Astronomy

University of Florida

Gainesville, FL 32611

R. W. Evans¶

OAO Corporation

7500 Greenway Center

Greenbelt, MD 20770

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†Research Scientist, Associate Fellow, AIAA

*Professor, Dept. of Mathematics

§Associate Professor, Dept. of Astronomy

¶Support Scientist

ABSTRACT

The effects of the sporadic meteroid environment on interplanetary spacecraft have an important impact on mission design. This paper describes a reformulation of the Divine interplanetary **meteroid model,** called METEM, that is capable of estimating many of those effects. METEM and the original Divine model it is based on made use of the new meteroid data obtained since the 1970s when the original NASA meteoroid models were developed to provide a comprehensive "phase space" description of the environment. METEM allows detailed estimates of the meteoroids' directionality and variation with distance from the Sun. It incorporates several different meteroid "populations", each population being described in terms of a distribution function in velocity phase space. These distribution functions are integrated along a spacecraft trajectory to give the meteoroid fluence as a function of velocity and angle relative to a specified surface. The paper explicitly compares METEM predictions of mission meteoroid fluences with those of the standard NASA models for 3 representative trajectories (an inner solar system, Helios-like mission, a mission at 1 AU, and a Cassini-like, outer solar system mission). In addition, the METEM model is used to estimate the angular variations in the meteoroid fluence expected along these trajectories--a unique feature of this new class of models that provides additional insights into how a spacecraft can be designed to protect it from meteoroids.

interplanetary meteors

NOMENCLATURE

A'	= Equivalent sensitive area
β	= the heliocentric latitude
C_o	= constant for shield material = 0.54 (for Al)
δ	= "delta factor"
e	= eccentricity
f	= asteroid population heliocentric variation in number density
F_c, f_c	= NASA model cometary fluence (particles/m^2) and flux (particles/m^2s)
F_a, f_a	= NASA model asteroidal fluence (particles/m^2) and flux (particles/m^2s)
f_p	= Penetrating meteoroid flux as function of time
G	= asteroid population heliocentric variation for the longitude function
h	= asteroid population latitudinal variation
H_m, H_M	= mass differential and cumulative distribution functions
η_D	= weighting factor for detector effects
i	= inclination
λ	= heliocentric longitude
m	= meteor mass (g)
N_1	= radial distribution (N_1 depends only on r_1)
p_e	= eccentricity distribution (p_e depends only on e)
p_i	= inclination distribution (p_i depends only on i)
ρ_c, ρ_a	= spatial density (particles/m^3); ρ_c=cometary, ρ_a=asteroidal
R	= heliocentric distance (AU)
r_1	= perihelion distance
ρ_m	= density of projectile (g/cm^3)
t	= small time interval
T	= time (mission duration)
t_c	= critical thickness of shield for which perforation will occur for particles equal to or greater than the critical size (cm).
$\langle V_c \rangle$, $\langle V_a \rangle$	= NASA model cometary and asteroidal relative impact velocities (km/s)
v_D	= speed with respect to detector
V_m	= Impact speed (km/s)

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INTRODUCTION

Collisions with meteoroids have been a concern for spacecraft designers since the early days of the space program. The sources of these particulates are believed to be the debris from asteroids and comets or the ejecta from collisions of meteoroids with large bodies such as the Earth or Moon. Given the pervasive nature of meteoroids, the effects of the macroscopic particulate environment must be quantified over the lifetime of a space system to project the life expectancy of exposed mechanical and electrical systems. For the last two and a half decades, the primary tools for modeling the meteoroid environment have been the models described in NASA SP-8013[1] and NASA SP-8038[2]. New data, primarily from Helios, Voyager, and Earth-based radar have become available since these models were formulated. In addition, the older models do not readily lend themselves to the determination of impact as a function of angle relative to a surface normal (the models basically assume all impacts are at normal incidence) nor to a determination of an accurate distribution of impact velocities with direction and mass (note: the older models do allow for an approximation to a distribution of velocities through the so-called "delta function"). The need to incorporate the latest meteoroid data and to model the angular variations in the meteoroid fluence for interplanetary missions led to the development a more detailed model by Dr. N. Divine in the early 1990's[3]. Since then, that model has seen wide acceptance in the international community. Unfortunately, the model has proven difficult for general use and requires intimate knowledge of the code to modify it and incorporate new results or features. This paper will describe tests of a reformulation of the Divine meteoroid code called METEM (for METeoroid Engineering Model) recently developed to address these issues. The results of that code will be compared with the older NASA models and the new angular and velocity distribution features will be exploited to illustrate the practical value of the model.

METEOROID MODELS--GENERAL CONSIDERATIONS

In practice, methods for modeling the meteoroid environment fall into 3 groups:

1.) Modeling of single particle dynamics where the trajectories of individual particles are followed. This resembles the plasma physics "particle in box" approach and is used where, in the case of asteroids, there are a few well defined "particles".

2.) Models of organized "streams" (i.e., meteor streams), "rings" (i.e., Saturn's rings) or "shells" (Earth space debris that has been randomized at a fixed orbital altitude).

3.) Algorithmic fits to the background, random environment. This is primarily the so-called sporadic meteors or the zodiacal light.

In principle, the single particle physics applicable to the asteroids can be used to model any meteoroid environment. Unfortunately, models of the sporadic meteroids or even the rings of Saturn would involve the tracking of millions of particles to adequately describe the actual environments--thus the need for some form of simplification. The algorithmic models on the other hand tend to only permit calculations of the specific quantities to which they have been fit. Here, after a brief review of the algorithmic fits characteristic of the NASA models, the new, phase space density approach developed by Divine will be presented. The phase space density description, while allowing simplification of the overall problem, also permits the derivation of many if not all the quantities necessary for studying the effects of the meteoroid environment on spacecraft.

In the following development, one problem in particular should be kept in mind--that of the "penetration speed" or, less accurately, "impact velocity". The precise definition of "impact velocity" has proven to be difficult as the actual particulate environment is characterized by a velocity distribution rather than a single impact velocity assumed in the earlier models. Based primarily on how the impact velocities should be weighted when taking a mean or average, variations in estimates of the effects of impacts are possible. The problem is due to the fact that the minimum mass capable of causing failure varies with velocity--typically decreasing with increasing velocity. In practical terms, the “average” velocity will often differ from a weighted velocity required for impact probability calculations. A second issue arises because the average impact velocity and meteoroid fluence both vary in time (or position) during the spacecraft mission so that the probability does not increase linearly in time but in a complex fashion. The actual value of the impact velocity to be used will depend on the orbital position of the spacecraft and its instantaneous velocity vector. The precise treatment of this velocity and the velocity distribution function pose an uncertainty in the following calculations. The NASA and Divine models treat this issue in different fashions as will become apparent.

NASA INTERPLANETARY METEOROID MODELS

The current NASA meteoroid models do not attempt to treat individual particles, but, like the algorithms or numeric expressions that define the neutral atmosphere, are fits to observations. They therefore represent a very compact, though physically limited, representation of the meteoroid environment--specifically the models provide a number density as a function of mass and a characteristic velocity or speed from which flux and fluence can be derived. As of this date, the NASA models are the accepted engineering meteoroid environment "tool". The principle documents describing these models are the "NASA Space Vehicle Design Criteria (Environment); Meteoroid Environment Model (Near Earth to Lunar Surface)"[1] and "NASA Space Vehicle Design Criteria (Environment); Meteoroid Environment Model (Interplanetary and Planetary)"[2].

The first document defines the meteoroid environment between the Earth's surface and the Moon in terms of simple numeric expressions. It provides working definitions of the three principle quantities needed to define the meteoroid environment: their mass versus number density, their velocity distribution, and their density (composition). Included in the document are listings of interplanetary meteor streams (the "predictable" component) and the Earth-based meteor observations on which the "sporadic" models (sporadic is taken here to mean the background flux of meteoroids that are basically random) are based. The second document presents an extrapolation of the Earth-based observations to interplanetary space for sporadic meteoroids of different "origins"—cometary and asteroidal. These models of the sporadic meteors have served well for almost 25 years and only as new data on the interplanetary meteoroid environment have become available were changes in these models proposed[3,4]. As these NASA meteoroid environment models are currently still the basis for most engineering studies of the effects of the meteoroid environment, they will be briefly described.

Meteoroids as defined by the NASA documents are solid particles orbiting in space that are either of cometary or asteroidal origin. The spatial volume of interest ranges from 0.1 to 30.0 astronomical units (AU). The mass range is from 10^{-12} to 10^{2} g. Knowledge of these particles is based primarily on Earth-based observations of meteors, comets, asteroids, the zodiacal light, and in-situ rocket and spacecraft measurements. The flux versus mass of the particles, the basic quantity required to model the meteoroid environment, is not directly measured but must be inferred (e.g., from light intensity, crater distributions, etc.). The ground-based measurements consist principally of photographic and radar observations. The sporadic meteoroid component is divided into those of cometary origin and those of asteroidal origin. The distinction between these two groups will become clear in the following.

COMETARY METEORS

In terms of the NASA models, cometary meteoroids in the mass range of interest (<100 g) are believed to be the solid remains of large water-ice comets that have long since evaporated or broken up due to collisions, or simply fragmented/dispersed from comet surfaces without destroying the comet. The remaining silicate or chondritic material is of very low density (0.16 to 4 g/cm^3) with an assumed value of 0.5 g/cm^3 for the NASA models. The primary flux inside 1.5 AU is made up of these cometary meteoroids. NASA 8038[2] describes the integral cometary meteor number density (ρ_c) for a mass m or larger by:

$$\mathrm{Log}_{10}(\rho_c) = -18.173 - 1.213\ \mathrm{Log}_{10}(m) - 1.5\ \mathrm{Log}_{10}(R) - .869\ |\sin(\beta)| \qquad (1)$$

The "average" impact velocity to the surface, as a function of spacecraft orbital parameters "σ" (the ratio of the heliocentric spacecraft speed to the speed of a circular orbit at the same distance from the Sun), "θ" (angle between spacecraft velocity vector and circular orbit in same plane), U_c (a cometary velocity function described in NASA 8038[2]), and R (distance from Sun in AU), is given by:

$$<V_c(\sigma, \theta, R)> = R^{-1/2}\, U_c(\sigma, \theta) \tag{2}$$

This velocity is assumed to be normal to a surface for the NASA models when calculating impact effects.

Once a number density is determined and the impact velocity computed, the cometary flux to a randomly tumbling plate can be estimated by the following simple formula:

$$f_c = 1/4\ \rho_c <V_c> \delta^{-1} \tag{3}$$

The total fluence, F_c, is the integral of f_c over time. The "delta factor" is a small correction factor (on the order of 1 typically) included to account for the fact that there is a distribution of velocities. It is given as a function of σ and θ in NASA 8038[2].

ASTEROIDAL METEORS

As for the cometary meteoroids, the basic computation of the asteroidal flux follows three steps: determine the penetrating mass based on the particle density and impact velocity, determine the number density at the given mass, and compute f_a (the asteroidal flux) from $1/4\ \rho_a<V_a>$. Unlike the cometary population of meteoroids, however, which is assumed to be fairly uniform in its characteristics with heliocentric distance, the asteroidal component shows a marked heliocentric variation in number density. Visual observations down to masses on the order of 10^{19} to 10^{20} g demonstrate the existence of the well-known asteroid belts between roughly 1.5 and 3.5 AU. It was assumed from the comparative (with respects to the cometary meteoroids) rarity of asteroidal meteoroid falls at the Earth that the lower mass component of the asteroidal meteoroids is similarly confined to the 1.5-3.5 AU range. From laboratory studies of presumed asteroidal meteorites, the density of these particles averages about 3.5 g/cm^3--substantially denser than the cometary meteoroids. (Note: observations[4] on Pioneer 10 and 11 imply that this population does not exist at masses below 10^{-9} g--see blue-ribbon panel recommendations below--and, by extrapolation, may not exist in the mass range of interest to impact studies.)

In parallel with the cometary meteoroid model, NASA 8038[2] provides functional relationships for the variation of the asteroidal meteoroids with relative impact velocity, heliocentric longitude, and heliocentric latitude. U_a and $<V_a>$ are the asteroidal versions of U_c and $<V_c>$. U_a and $<V_a>$ are related by:

$$<V_a> = R^{-1/2}\ U_a \qquad (4)$$

Unlike U_c, U_a and its relationship to σ and θ vary with R. NASA 8038[2] lists three different variations for U_a corresponding to R = 1.7 AU, R = 2.5 AU, and R = 4.0 AU. As a final component of the asteroidal model, δ is also introduced but as this is so close to 1 (the asteroidal meteoroids have a very sharply peaked velocity distribution function), it is ignored in the NASA model. Again, all variations are assumed to be essentially independent of each other so that the flux is the product of all the components. For the mass range of interest, the resulting equation is:

$$\mathrm{Log}_{10}(\rho_a) = -15.79 - .84\ \mathrm{Log}_{10}(m) + f(R) + G(R)\cos(\lambda) + h(\beta) \qquad (5)$$

As before:

$$f_a = 1/4\ \rho_a <V_a> \qquad (6)$$

GALILEO METEOROID MODEL

An important revision to the NASA models was a version developed for the Galileo mission. To reflect Pioneer in-situ meteoroid observations[4], the NASA models were modified by a blue-ribbon panel convened by NASA between 1978 and 1980 to incorporate the latest Pioneer 10/11 meteoroid data for the Galileo mission. The major recommendations of the panel were as follows:

1. Based on the Pioneer results, which indicated the absence of an asteroidal component at masses below about 10^{-9} g, the panel recommended that only the cometary component be considered.

2. The NASA cometary meteoroid model spatial density has a $R^{-1.5}$ dependence. As a conservative assumption, the panel recommended assuming a constant density twice that of the NASA cometary

model at 1 AU between 1 and 5 AU. (It has since been tacitly assumed that the factor of two and constant density also be applied within 1 AU.)

3. As in the case of the NASA cometary meteoroid model, the flux was assumed to be isotropic.

4. The so-called "δ factor" which takes into account the cometary relative velocity distribution is assumed to be $\delta = 1$.

Of the assumptions, the elimination of the "δ factor", used to correct for the velocity distribution, has caused the most concern. The consequences of this effect were found to be minimal, however, in direct comparisons with the results of the original NASA cometary model which included the factor and this "Galileo model" which did not.

DIVINE MODEL

Whereas the NASA models are empirical fits to the mass distribution and average impact velocity, the model developed by Divine[3] takes as a starting point the particle phase space density. To make this clear, consider first the fundamental physical concepts associated with meteoroids. The physics of macroscopic particles in principle resemble that of a charged plasma environment as gravity, the principle controlling force (light pressure and electrostatic forces are ignored in this paper but they can be very important for the smaller or low density particles), varies as the inverse of the distance between interacting objects just as in the case of electrostatic forces. It is common practice in defining the characteristics of a plasma to define a phase space distribution function. In particular, a particle in space has a mass m, a position vector r (with components x,y,z), and a velocity vector $v = dr/dt$ (components v_x, v_y, v_z). A particle population can be represented by a continuous distribution defined by:

$$dN = [H_m dm]\left[g_o(dxdydz)(dv_x dv_y dv_z)\right] \tag{7}$$

where dN is the mean number of particles with mass, position, and velocity in the intervals $(m,m+dm)$, $(x,x+dx)$, ..., (v_z,v_z+dv_z). The (x,y,z,v_x,v_y,v_z) are in heliocentric coordinates.

In the Divine model, the dependence on mass m is assumed to reside exclusively in the function H_m (independent of r and v). It is related to the cumulative mass distribution, H_M, by:

$$H_M = \int_m^\infty H_m dm \tag{8}$$

and g_o is a density in position-velocity space like that for a gas or plasma and is independent of m and t. For meteoroids, g_o can be taken as a function of the constants of motion in a gravity field (e.g., the six Keplerian orbital elements). In particular, it can be shown that g_o can be described for the interplanetary meteoroids as

$$g_0 = \frac{1}{2\pi e}\left(\frac{r_1}{GM_o}\right)^{3/2} N_1 p_e p_i \tag{9}$$

Given the distributions for p_i (the inclination distribution function), p_e (the eccentricity distribution function), and N_I (the radial distribution function), Divine[3] demonstrated that one can derive particle concentrations, fluxes (as functions of angle), fluences, and impact velocities (as functions of angle) along an orbit. The concentration, for example, is given by:

$$N_M = H_M \sum_{l=1}^{4} \int dr_1 \int de \int di \cdot g_0 \frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)} \tag{10}$$

where:

l = 1-4 (represents 4 possible particle directions)

The flux is given by:

$$J_M = \sum_{l=1}^{4} \int dr_1 \int de \int di \cdot g_0 \frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)} \cdot (\eta_D v_D)_l \tag{11}$$

For all impacts that contribute to the flux, the "mean velocity" (impact velocity here) is given by dividing the integral of the flux times the velocity by the flux[3] (Eq. 11):

$$\langle v_D \rangle = \frac{1}{4\pi J_M} \sum_{l=1}^{4} \int dr_1 \int de \int di \cdot g_0 \frac{\partial(v_x, v_y, v_z)}{\partial(r_1, e, i)} \cdot (\eta_D v_D^2)_l \tag{12}$$

DATA INPUTS TO DIVINE MODEL

The Divine meteoroid model represents a much more comprehensive representation of the environment than the earlier NASA models. It can be used to describe a complex number of variations and populations simultaneously. Indeed, based on the preceding concepts, Divine was able to fit almost all of the existing meteoroid data. These data sets included: the Interplanetary Flux Model of Grün, the Pioneer 10/11 data set, the Helios fluxes/events measurements, the Galileo Dust Detector, data from the Ulysses Dust Experiment, radar meteor observations, and estimates of the distribution of the zodiacal light population. The data sets, their sources, and distance and mass ranges are listed in Table 1.

Divine found that 5 distinct "populations" were necessary to fit the data. In particular, the "core population" is the best single population fit to the data and reproduces the Galileo data. The "inclined population" is fit to portions of the Helios data not described by the core population. The "eccentric population" fits the variations in the Helios data not fit by the other two populations. The "halo population" fits the Pioneer and Ulysses data sets. The "asteroidal population" fits Grün's Interplanetary Flux Model at large masses and the non-zodiacal light component of the meteor data. The appropriate distributions corresponding to these "populations" are presented in Figs. 1–4. The densities assumed for these populations are .25 g/cm^3 for the eccentric population (note: this population contributes very little to any of the fluence calculations and can be ignored in general) and 2.5 g/cm^3 for all the others. Figures 1-4 define the distribution curves for each population. These curves and the definition of density compromise the basis of Divine's meteoroid model. Flux, fluence, impact speed, etc. are all computed using these curves and Eqs. 7-12.

METEM MODEL

Despite its many advantages, the Divine model as originally formulated and coded has proven difficult to utilize and manipulate. There has been growing interest, however, in its use and further development. In particular, Matney and Kessler[13] showed that Divine's original formulation of p_i,

p_e, and N_I do not correspond to "textbook" definitions of the particle distribution functions--Divine's $p_i\ di$ is not, for example, the number of objects with inclinations between i and $i+di$. They find that the proper normalizations should be:

$$N_I{}' = r_I{}^2 \bullet N_I\,, \qquad p_i' = \sin i \bullet p_i\,, \qquad p_e' = p_e/(1\text{-e})^{3/2} \qquad (13)$$

where the primed quantities correspond to the textbook definitions.

In addition to these suggested changes in normalization, Taylor[14] and colleagues have suggested that the original analysis of Sekanina and Southworth[9] of the radar meteors may have been flawed. It is suggested that an error in the bias-corrected values of the encounter velocities has been identified. This error is traced to an apparent typographical error in a formula where a value of 1.86 should have been 1.36. As of this date, it is not clear whether or not the error is real. The data do, however, form an important part of the Divine model data base and when this is issue is settled it may be necessary to update Divine's original distributions.

To address these two issues and to make the Divine model more accessible, the authors have developed a new formulation of the Divine model. The new model, called METEM, directly addresses the concerns of Matney and Kessler. Starting with the original distributions of Divine, the METEM model converts them internally into the normalizations of Eq. 13 which are then used in all subsequent computations--a user can thus input either the original distributions or those in Eq. 13. In addition, numerous ambiguities, singularities, and issues of precision have been corrected. A special version of METEM has also been developed that can be used to vary the Sekanina and Southworth data inputs to test the effects of Taylor's proposed correction. This version will be used to develop corrected versions of the distributions functions--Divine's or Matney and Kessler's versions--when a consensus is reached on the correct interpretation of that data. Finally, a user friendly front end in Visual Basic® has been developed for METEM that makes input and output straightforward. The METEM formulation and its user friendly METEMvb version have been carefully tested against the original Divine model and yield similar results over the same range of inputs.

METEM is not the only on-going effort to revise and upgrade the original Divine model. Indeed, Staubach, Grün, and Jehn[15] (see also Grün et al.[16]) have investigated the effects of solar radiation pressure on the distributions for masses less than 10^{-10} g and produced revisions to the original Divine model that take these effects into account. They are not included in METEM as the impact of the particles in this range typically have little or no effect on spacecraft performance--the primary use of the NASA and METEM models.

NASA-METEM COMPARISONS

The NASA models have been the baseline meteoroid models for over 25 years. As such, it is of real value to potential users to compare the predictions of these models with those of the newer Divine model as represented by METEM. Given the different formulations and data sources, it is only to be expected, however, that there will be observable differences between the models. To compare the models on an equal bases, 3 representative mission scenarios were selected: 1) a spacecraft in Earth orbit (in the absence of the Earth); 2) a representative Cassini trajectory to Saturn; and 3) an inner solar system mission--Helios. These orbit scenarios are illustrated in Figs. 5 and 6.

A primary use of meteoroid models is to predict the integral fluence for a given mass threshold or to estimate the probability of a system failing due to meteoroid impact. The former requires calculating the fluence of particles with a mass m or higher onto a (typically) randomly tumbling plate. As an adjunct, the "average" impact speed is usually desired. In the latter case, one requires a definition of a "failure criteria". Typically this is a surface penetration formula that describes the relationship between the mass and velocity of a meteoroid that just fails a tank, battery, solar cell, etc. Here the well-known single surface penetration formula for thin plates[17] for particles from 50 µm to ~1 cm diameter impacting aluminum will be assumed. The thin plate formula is based on empirical fits to data and gives the minimum thickness necessary to prevent perforation for a given mass/velocity combination:

$$t_c = C_o \rho_m^{1/6} m^{.352} V_m^{.875} \qquad (14)$$

V_m is assumed to be the average impact velocity for the NASA models as given by Eqs. 2 and 4 (it is defined by these models to be normal to the surface). For METEM, V_m is assumed to be the absolute magnitude of the velocity vector relative to the surface. METEM gives the actual impact velocity vector relative to the surface but this definition was selected so as to give a worst case. To illustrate the calculation of a mission failure probability, it will be assumed that t_c is the thickness of an aluminum shield that would just be perforated by a 1 g particle of 2.5 g/cm^3 density and impact speed of 20 km/s. All other densities, masses, and velocities of impacting particles will be scaled according to Eq. 14 using this thickness to determine if they would cause failure (that is, any particle mass/velocity combinations requiring a smaller thickness than t_c will be assumed to not cause failure).

Once a failure criterion is established, the total fluence at each trajectory position to a randomly tumbling plate is estimated over the entire range of velocities and masses that cause surface penetration. The probability of failure is then computed from an estimate of the appropriate sensitive area multiplied by this critical fluence. In statistical terms, the probability of X impacts on a spacecraft is given by:

$$P(X,t) = \frac{(f_p A' t)^X e^{-f_p A' t}}{X!} \tag{15}$$

Here, rather then compute the probability of failure, the fluence for the critical mass m_c (impacts per unit area for the mass/velocity combinations that will just perforate a surface of thickness t_c) will be estimated as a function of mission duration for each model.

Figs. 7 and 8 compare the mission fluences for METEM and the three NASA models: the asteroid component (APROB), the cometary component (NASA), and the Galileo cometary model (GAL) for the three missions. Fig. 7 is the fluence of all particles with a mass of 1 g or higher while Fig. 8 is the fluence for all penetrating particles meeting the thin plate, single surface penetration formula, Eq. 14, criteria for a randomly tumbling surface.

The final mission fluences for Figs. 7 and 8 are tabulated in Table 2. The main points to note for these results are that the NASA asteroidal component typically dominates if the spacecraft passes through the asteroid belt between 1.5 and 3.5 AU. The Divine model estimates, which are the sums of 5 different populations, are 1/3 of the NASA cometary fluences for Helios, roughly equal for 1 AU, and higher (2 to 7 times) for Cassini for the 1 g mass threshold. Similar results hold for the penetration formula. Qualitatively, however, the Divine fluences follow the same patterns as the cometary model fluences as a function of mission elapsed time. The NASA asteroidal component exceeds the Divine model fluences by a factor of ~8 and follows a very different pattern.

While not unanticipated (the models are based on different data and distribution assumptions), the reasons for these differences between the models are of interest. Aside from the density differences (0.5 g/cm^3 for the cometary models; 2.5 g/cm^3 for 4 of the 5 Divine populations), the other important property is the average impact velocity. To study its behavior, the mean impact speed (estimated by Eqs. 2 and 4 for the NASA models and by the ratio of the integral of the product of the fluence and velocity divided by the integral of the fluence for the Divine model; see Eq. 12) has also been computed as a function of mission elapsed time. These values are plotted in Figs. 9–12.

The major contribution to the differences between the models in these estimates is that the impact speed for METEM is averaged over 5 populations. The individual populations for METEM have average impact speeds that cover a wide range of values (e.g., at 1 AU for a 1 g particle threshold, the speeds are: total--11.6 km/s; core--13.9 km/s; inclined--22.1 km/s; eccentric--23.6 km/s; halo--48.9 km/s; asteroid--11.5 km/s). Figures 9-10 reflect this averaging. In the NASA models, the velocity of the asteroidal component is significantly lower than that of the cometary components (the Galileo model has a different velocity than the NASA cometary model because of the δ factor). The NASA cometary component has a velocity close to the average impact speed for the Divine model for the 1 g threshold fluences. However, when a penetration relation is considered, the GAL and METEM velocities more closely agree. This agreement is most likely due to the increased weighting in the Divine model of the lower mass/higher velocity particle populations which dominate in the latter case because of their higher fluxes

FLUENCE ONTO AN ORIENTED PLATE

The final property to be presented is the variation in fluence as a function of orientation. Unlike the NASA models, the Divine model can explicitly estimate the fluence to a surface oriented in a fixed direction in space as opposed to the randomly tumbling plate. The ability to estimate the fluence to a surface is a valuable improvement as a spacecraft can be deliberately flown in a specific orientation to limit the impacts on a particular surface (a rocket nozzle or tank surface for example). Figs. 13-15 present estimates of the meteoroid fluence to a randomly tumbling surface, a surface oriented in the spacecraft velocity direction, and in a direction opposite to the velocity vector. (Note: the Divine model can calculate the actual impact velocity vector to a surface as a function of angle normal to the surface. We again assume a worst case estimate of the fluence in terms of the total impact speed into the oriented surface as opposed to just the normal component.)

The differences in fluence to the forward and tailward surfaces of a spacecraft are striking. For the Helios mission, when the spacecraft is moving slower than the circular orbit speed at aphelion, the spacecraft sees more fluence in the direction opposite the velocity vector and on its sides (as approximated by the randomly tumbling surface) than from the forward direction--the meteoroid flux is overtaking the spacecraft. For Fig. 14, at 1 AU, the flux to the sides (the randomly tumbling results) dominates--few particles are catching up from behind and fewer still are being overtaken. Finally, for the outer solar system missions, when the spacecraft is moving faster than the circular orbit velocity, the flux in the direction of the velocity vector dominates--the spacecraft overtakes the meteoroids. Note in particular the switch over in behavior around day 700 for the Cassini trajectory.

CONCLUSIONS

The new Divine model (in the form of the METEM code) produces results that at least subjectively resemble the older NASA meteoroid models. The differences in assumed populations, however, make a quantitative comparison difficult. Even so, this paper provides a link between the older models and the newer one that should prove useful for those seeking to compare their predictions. As a secondary objective, the paper has demonstrated the capabilities of the new model--in particular, its capability to estimate fluences to oriented surfaces. The Divine model is now available to the general community as the compiled METEM code that can be run on a wide range of PCs and main frame computers or with a Visual Basic front end (METEMvb) for use on Windows-based PCs. The reader is referred to the authors for copies of the code.

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TABLES

Table 1. Sources and ranges of input data for the Divine meteoroid model.[3]

		Heliocentric Dist (AU)	Mass (g)
IF Model[5]		0.98-1.02	10^{-18}-10^{0}
Pioneer 10[6]		1-18	$> 3x10^{-10}$
Pioneer 11[6]		1-9	$> 10^{-9}$
Helios[7]	fluxes:	0.31-0.98	$> 10^{-10}$
	events:	0.31-0.98	$> 10^{-14}$
Galileo Dust Det[8]		0.88-1.45	$> 10^{-13}$
Ulysses Dust Exp[8]		1.0 - 4.0	$> 10^{-13}$
Radar Meteors[9]		0.98-1.02	$> 10^{-4}$
Zodiacal Light[10]		0.3-1.0	10^{-8}-10^{-5}
	Ref 11	1	10^{-8}-10^{-5}
	Ref 12	3	10^{-8}-10^{-5}

Table 2. Total mission fluences for the Helios, 1 AU, and Cassini missions

Mission		Helios	1 AU	Cassini
Days		187.3	365.6	2447
Fluence (m >1 g) m^{-2}				
	METEM	4.48E-8	9.79E-8	1.40E-6
	APROB	0.0	0.0	8.73E-6
	GAL	1.55E-7	2.03E-7	1.06E-6
	NASA	1.41E-7	7.38E-8	2.01E-7
Fluence (m_c) m^{-2}				
	METEM	7.75E-8	3.39E-8	8.80E-7
	APROB	0.0	0.0	6.45E-6
	GAL	2.34E-7	7.13E-8	3.43E-7
	NASA	2.76E-7	2.59E-8	1.08E-7

FIGURE CAPTIONS

Figure 1. The Divine Model Eccentricity Distribution, p_e.[3] p_e is one of the functions used in Eq. 9 to define g_o.

Figure 2. The Divine Model Mass cumulative distribution, H_M.[3] See Eq. 8.

Figure 3. The Divine Model Radial distribution, N_1.[3] N_1 is one of the variables used in Eq. 9 to define g_o.

Figure 4. The Divine Model Inclination distribution, p_i.[3] p_i is one of the variables used in Eq. 9 to define g_o.

Figure 5. Trajectories assumed for the Helios and "1 AU" mission scenarios.

Figure 6. Trajectory assumed for a representative Cassini mission to Saturn--this is a VVEJGA or "Venus-Venus-Earth-Jupiter" gravity assist trajectory.

Figure 7. Fluence as a function of mission elapsed time for the Helios, 1 AU, and Cassini mission scenarios at a fixed mass threshold of 1 g.

Figure 8. Total fluence capable of perforating a fixed aluminum shield thickness as a function of mission elapsed time for the Helios, 1 AU, and Cassini mission scenarios. The shield was selected to have a thickness sufficient to protect against a 1 g particle of 2.5 g/cm^3 density at an impact velocity of 20 km/s (see Eq. 14).

Figure 9. Impact speed as a function of mission elapsed time for a fixed mass threshold of 1 g for the Cassini and 1 AU trajectories.

Figure 10. Impact speed as a function of mission elapsed time for a fixed mass threshold of 1 g for the Helios trajectory.

Figure 11. Impact speed for a fixed shield thickness for the Cassini and 1 AU trajectories (see caption for Fig. 8).

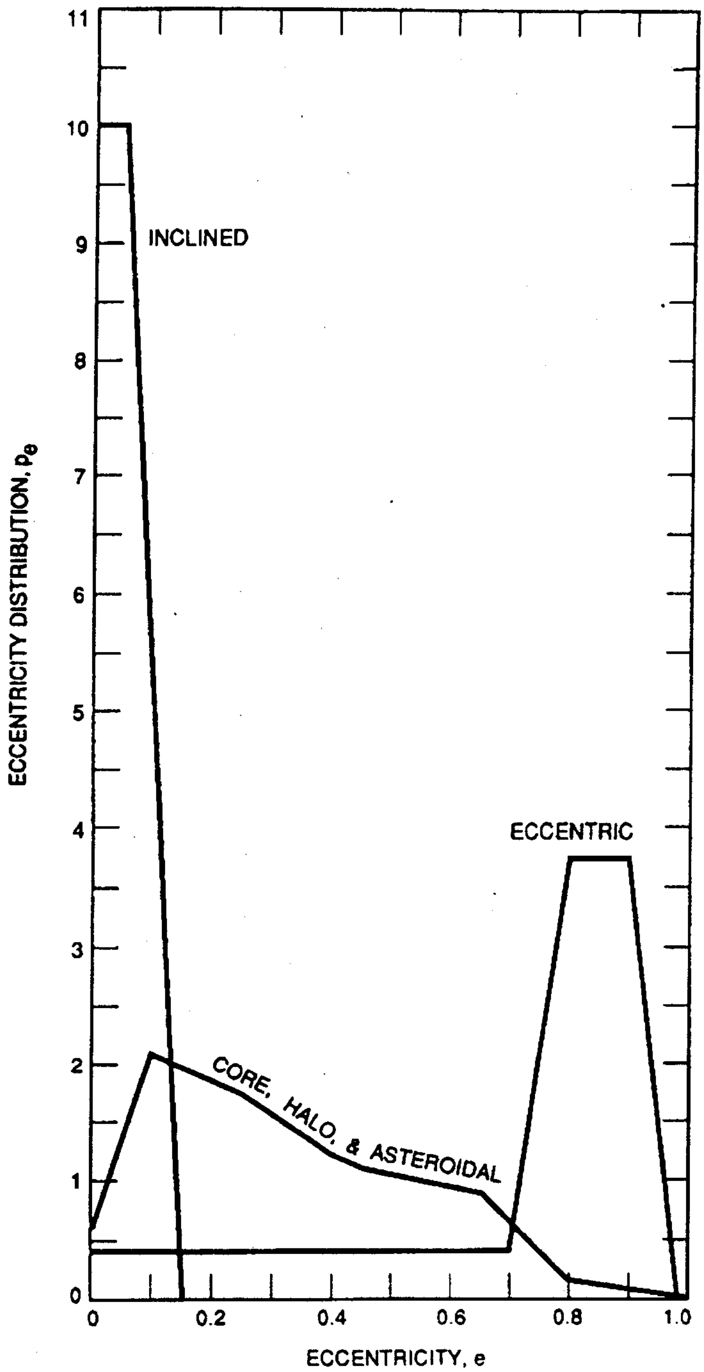
Figure 12. Impact speed for a fixed shield thickness for the Helios trajectory (see caption for Fig. 8).

Figure 13. Fluence for a fixed threshold of 1 g for the Helios mission trajectory onto a randomly tumbling plate. The fluence is compared for a surface oriented in the direction of the spacecraft

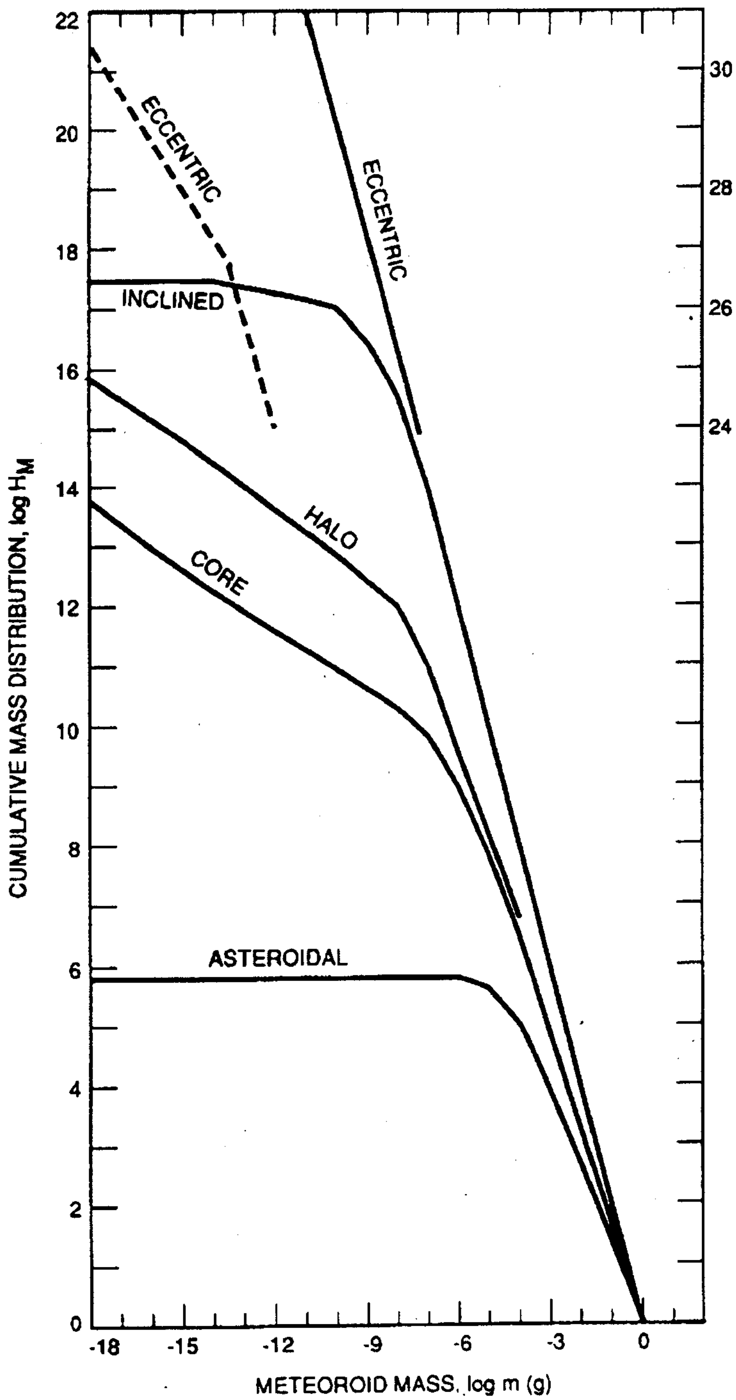
velocity vector (+V), for a surface oriented opposite to that direction (-V), and for a randomly tumbling plate.

Figure 14. The fluence (for a spacecraft at 1 AU) for a fixed threshold of 1 g onto a randomly tumbling plate compared to a surface oriented in the direction of the spacecraft velocity vector (+V) and opposite to that direction (-V).

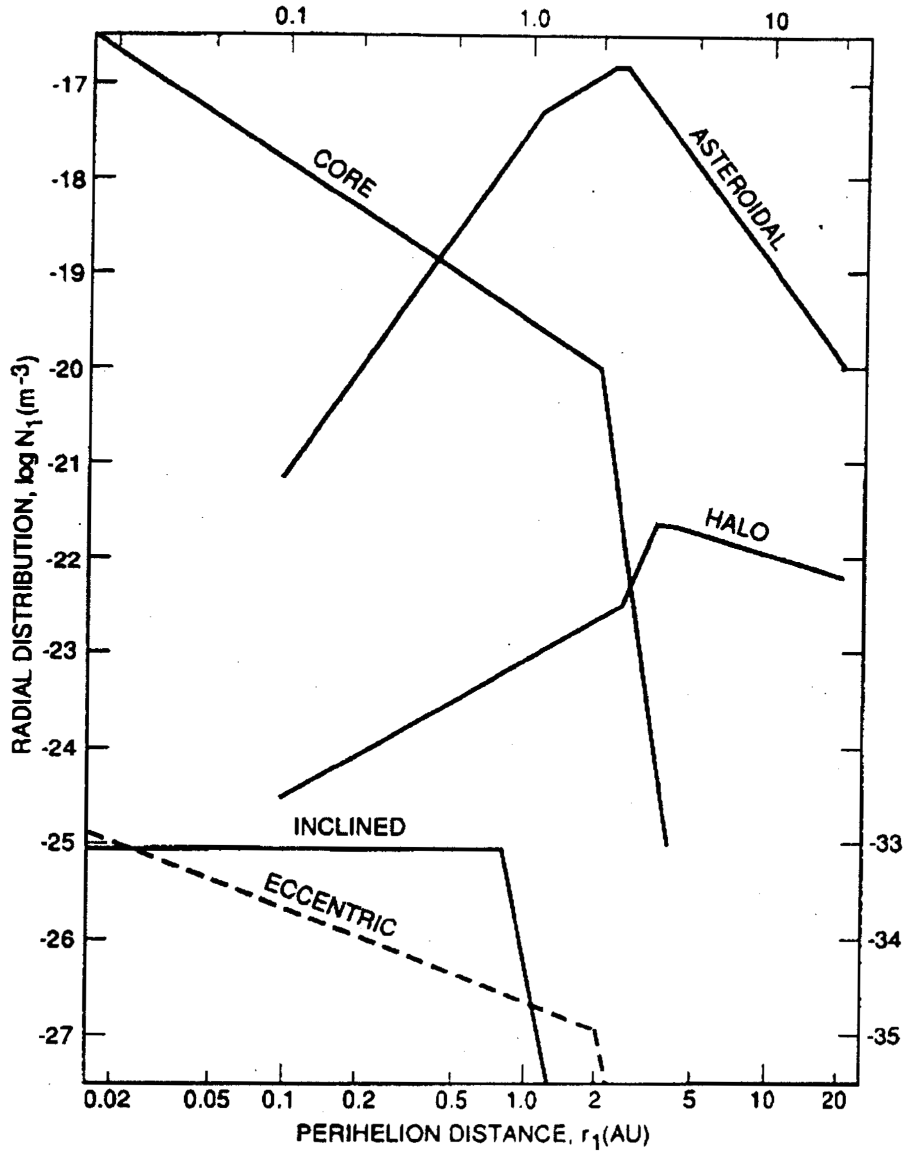
Figure 15. The fluence (for the a Cassini trajectory) for a fixed threshold of 1 g onto a randomly tumbling plate compared to a surface oriented in the direction of the spacecraft velocity vector (+V) and opposite to that direction (-V).



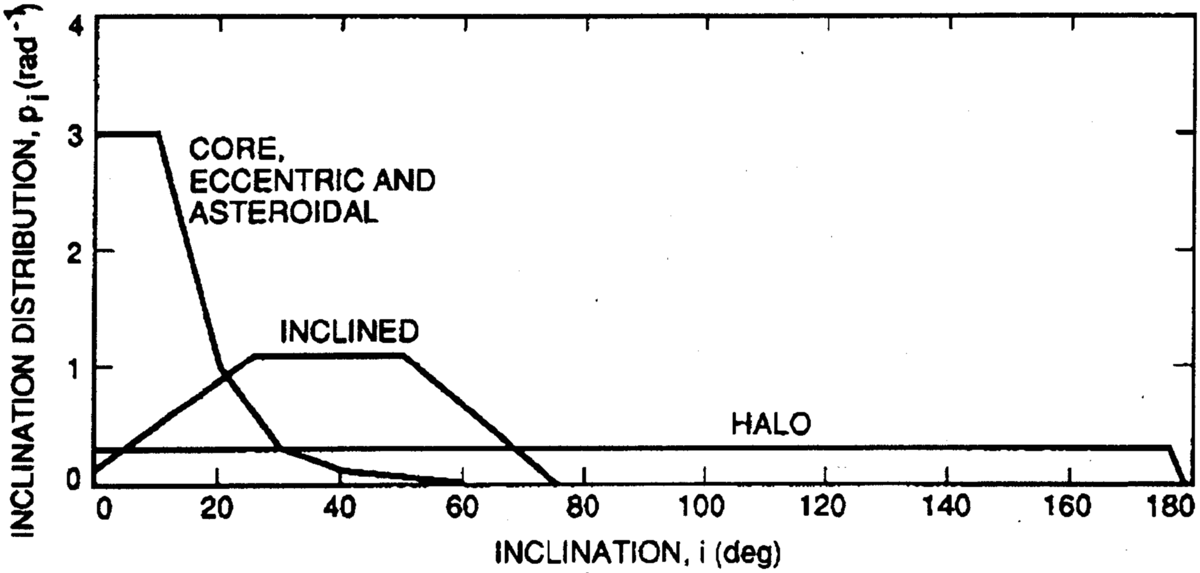
Henry Garrett, Fig. 1



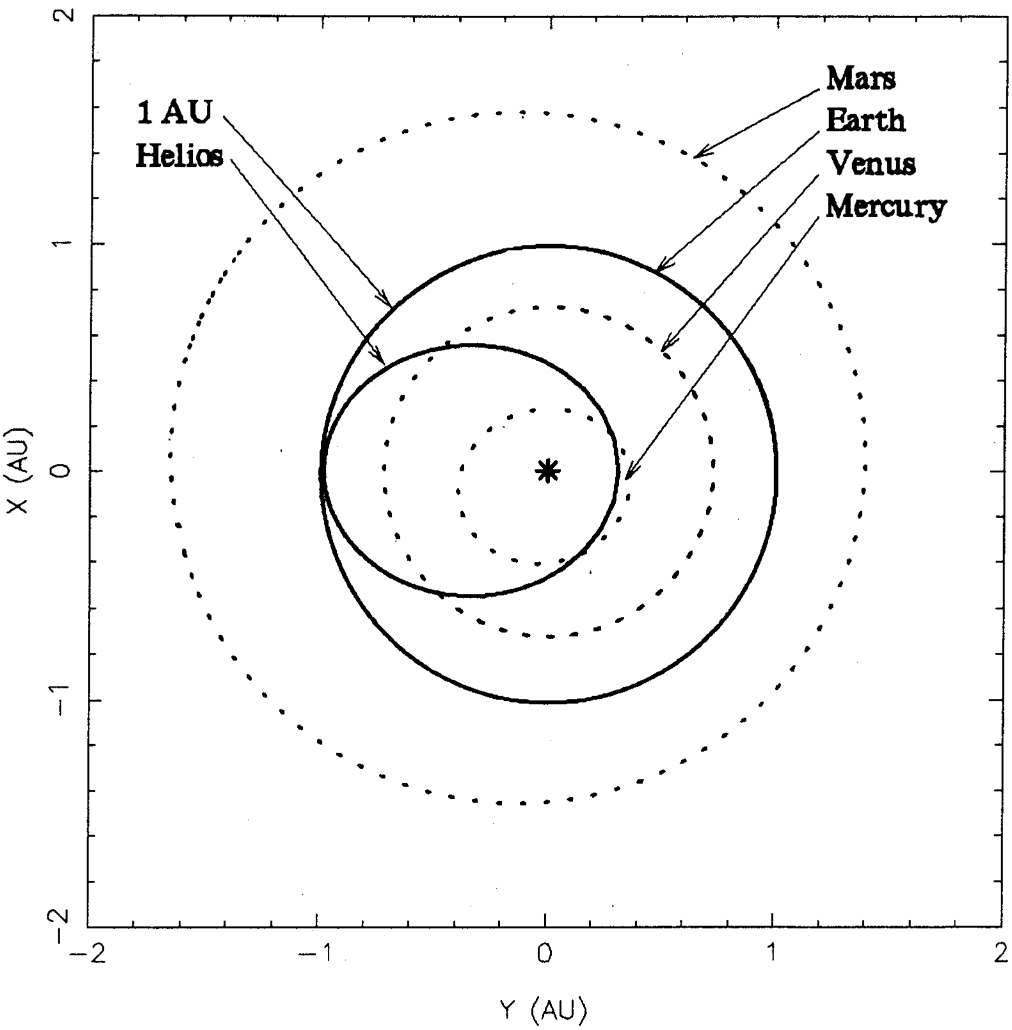
Henry Garrett, Fig. 2



Henry Garrett, Fig. 3



Henry Garrett, Fig. 4



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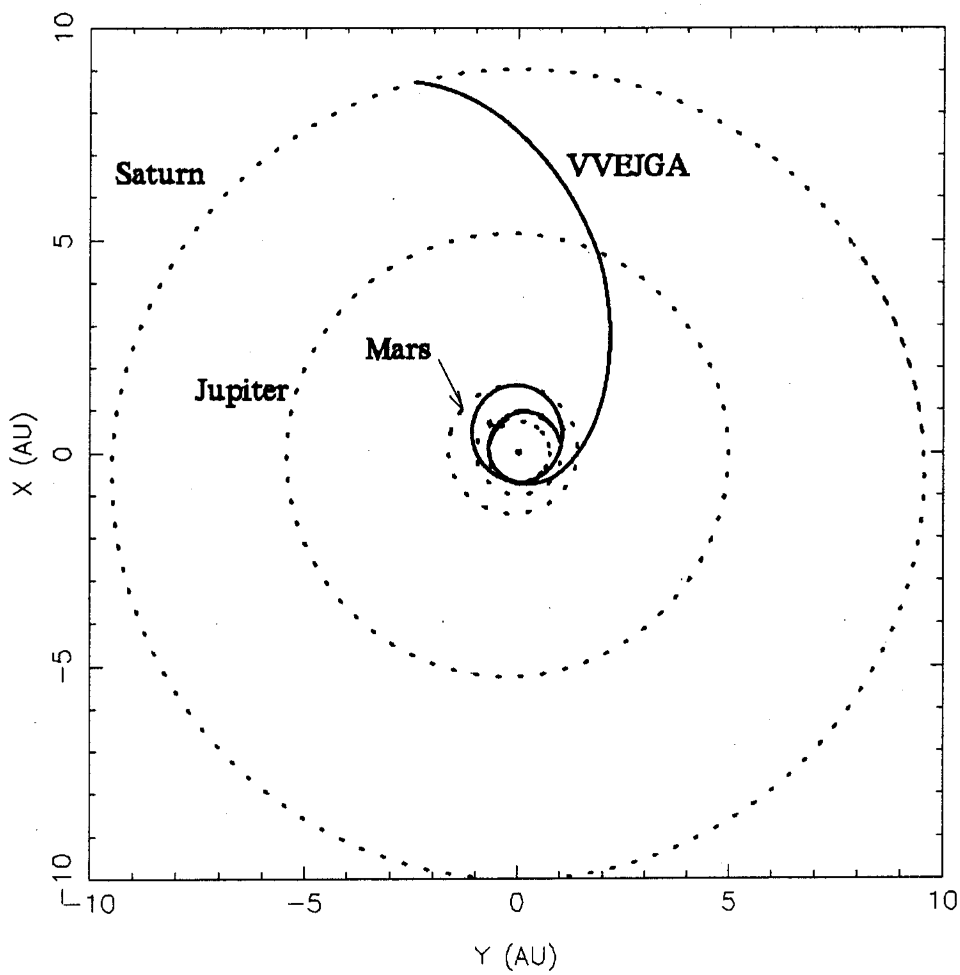
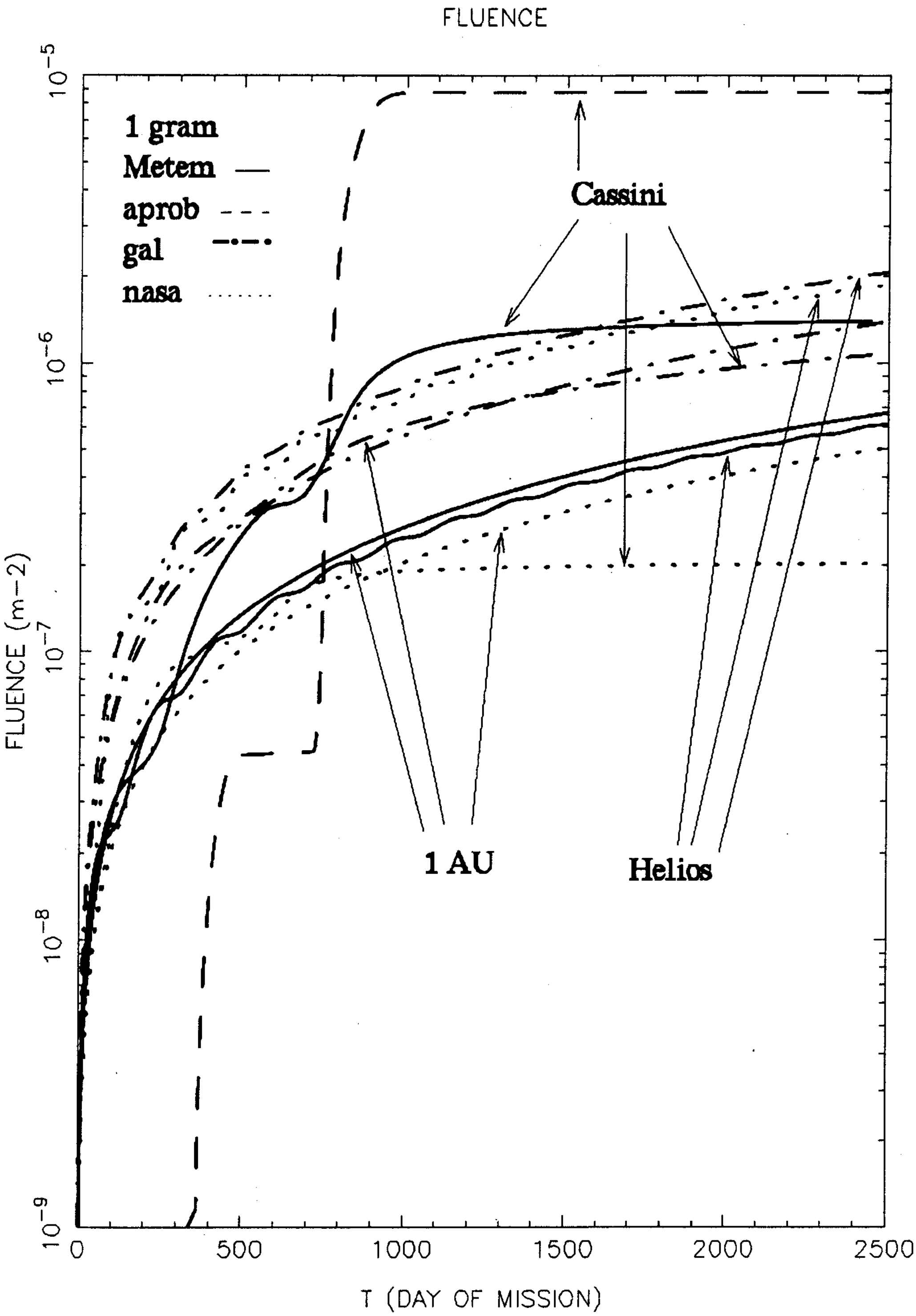
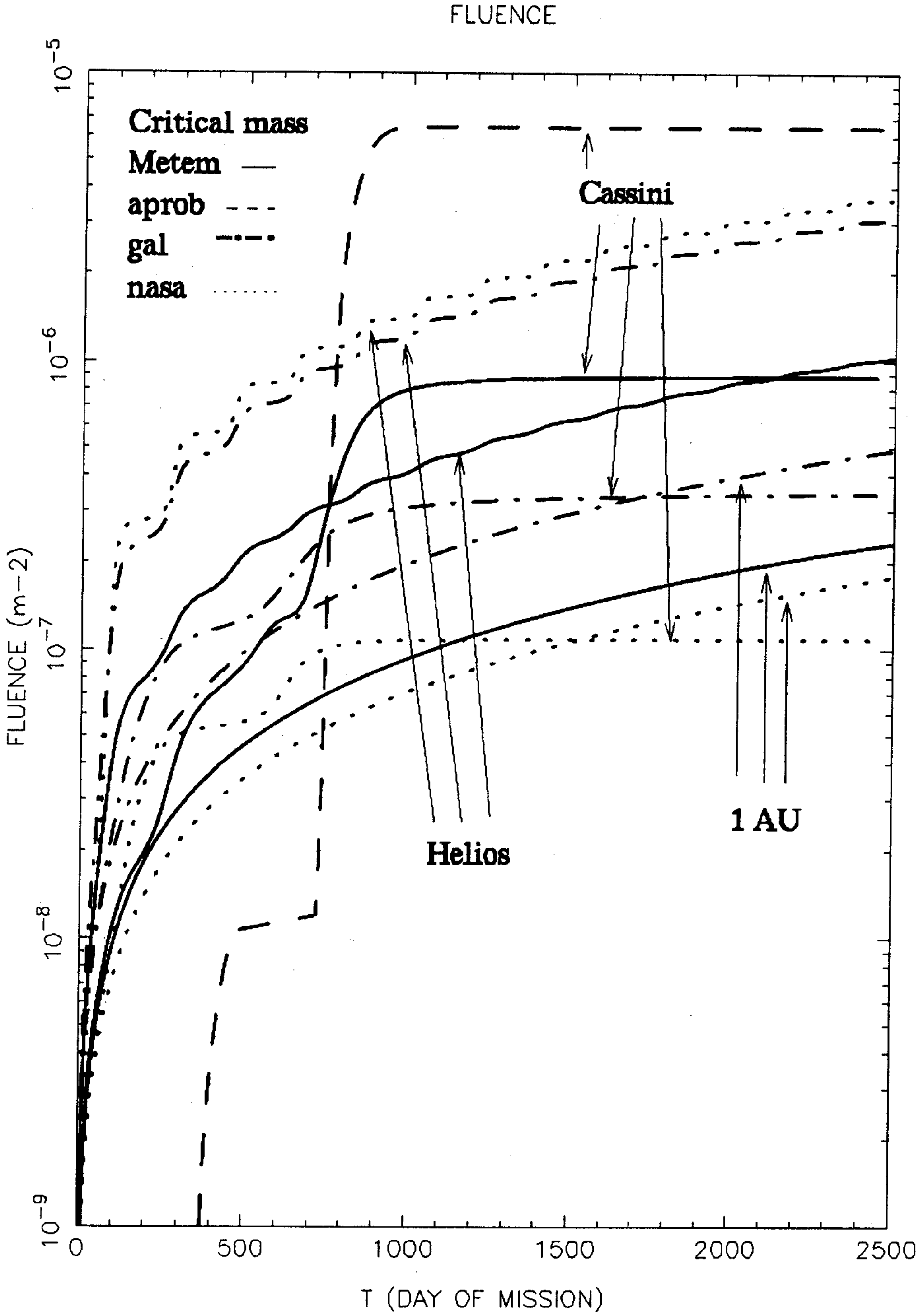


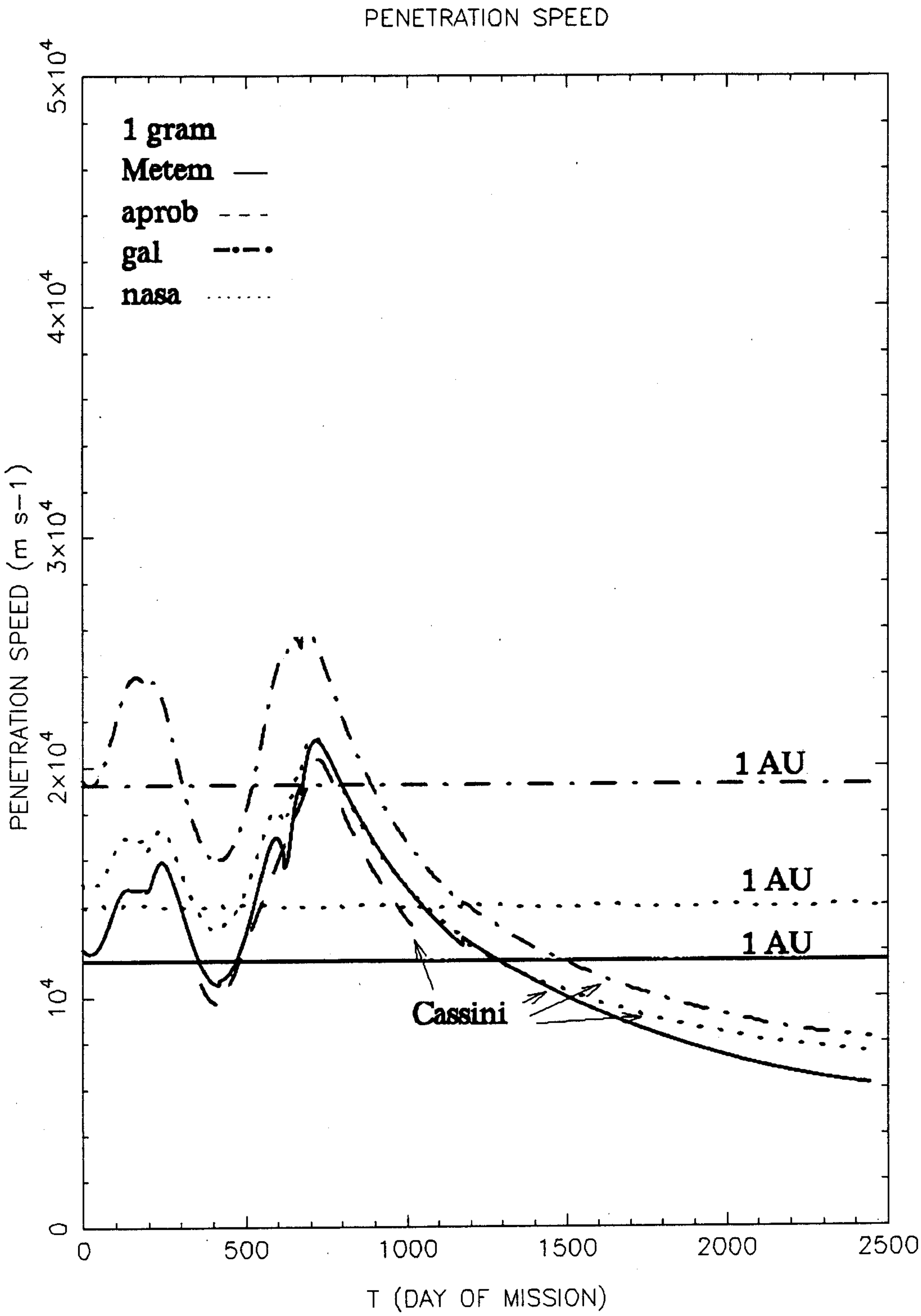
Henry Garrett, Fig. 6



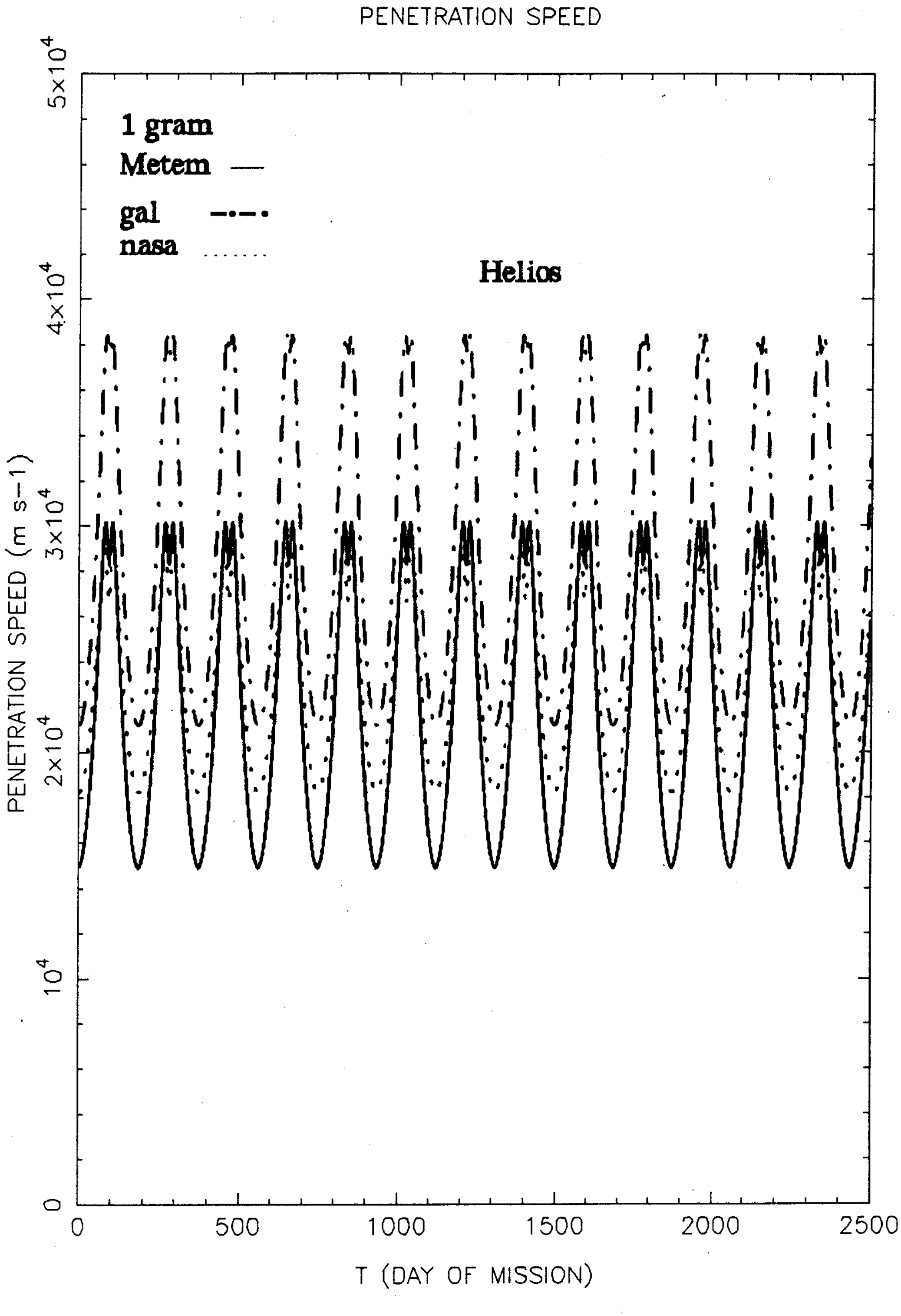
Henry Garrett, Fig. 7



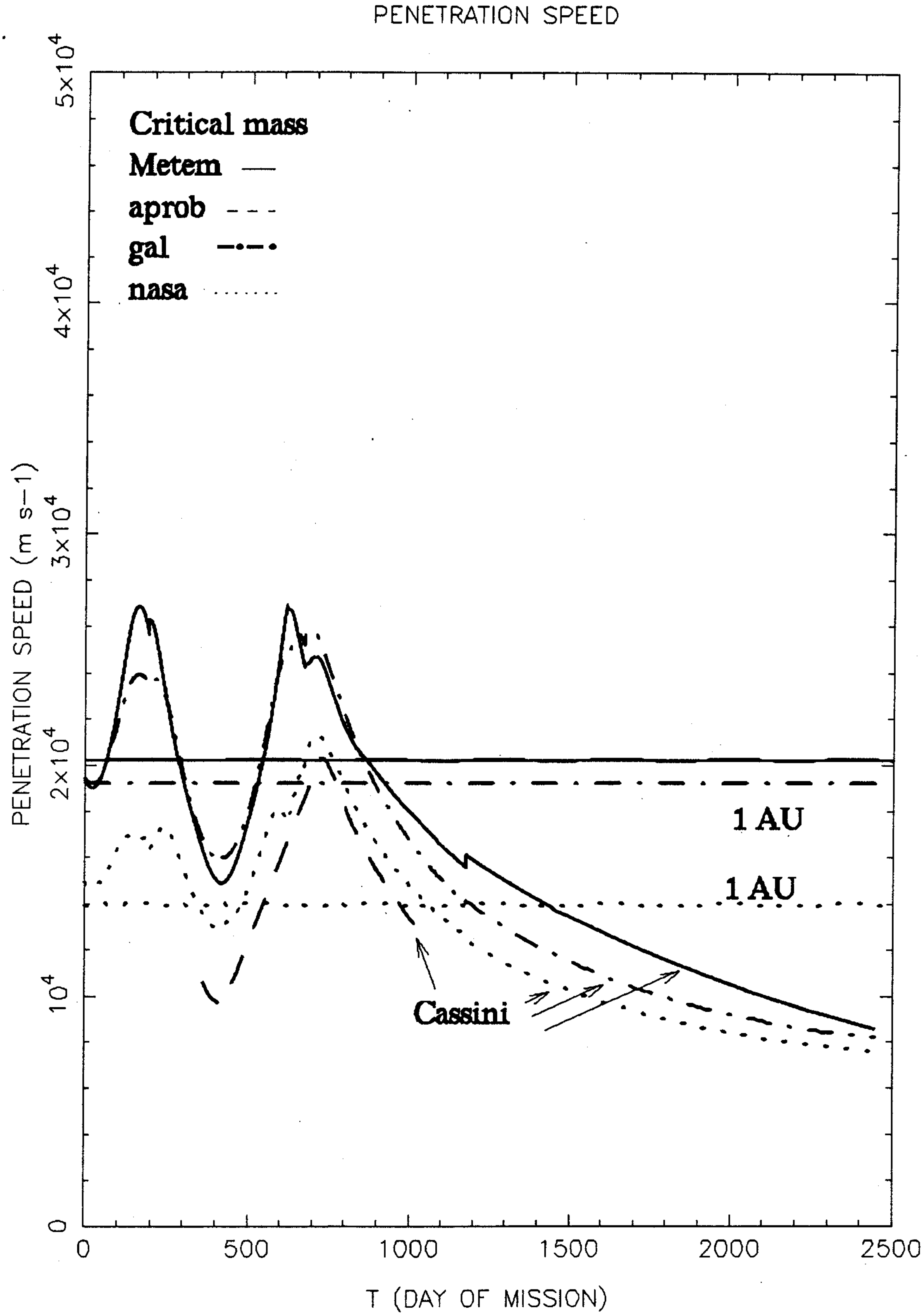
Henry Garrett, Fig. 8



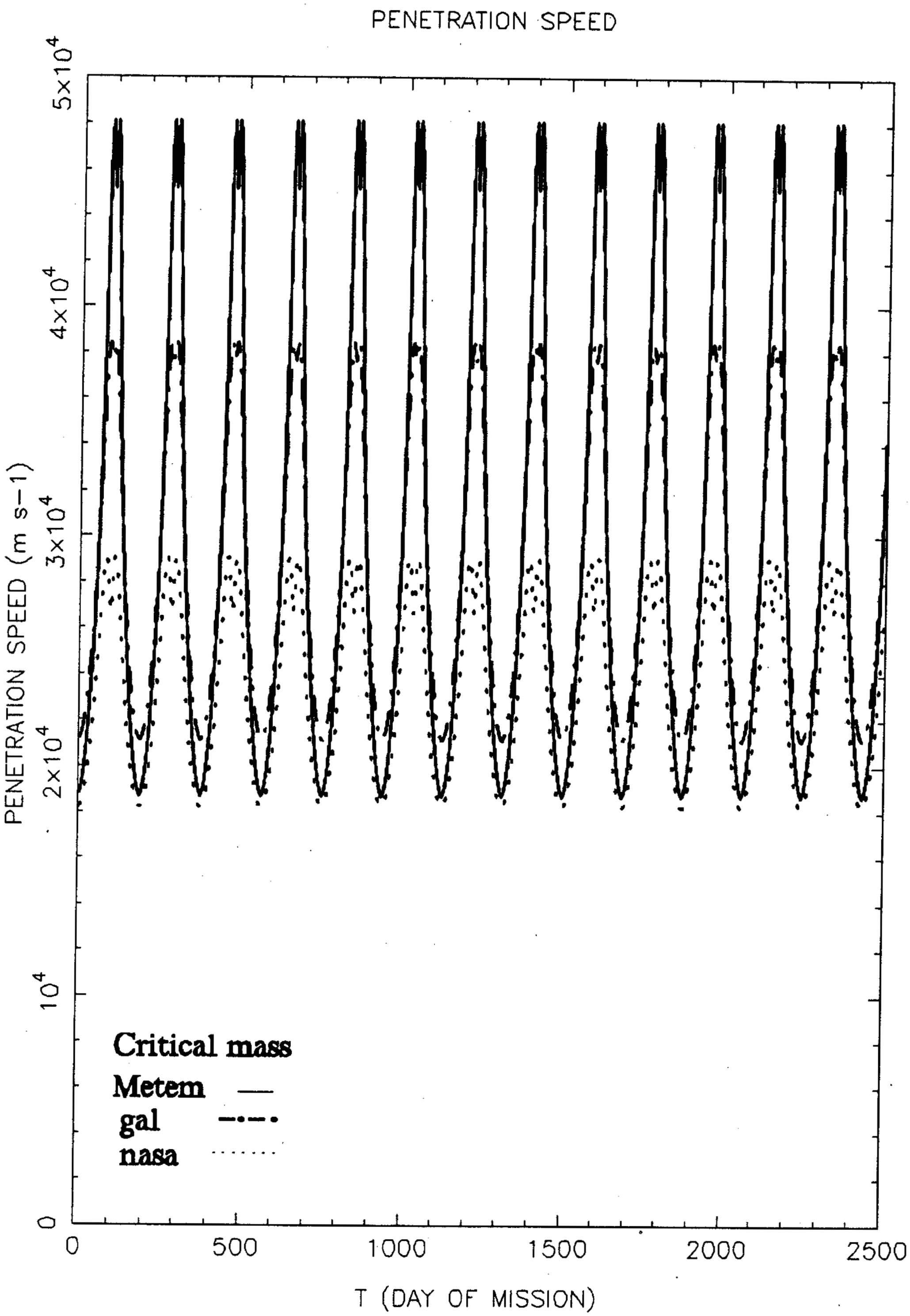
Henry Garrett, Fig. 9



Henry Garrett, Fig. 10



Henry Garrett, Fig. 11



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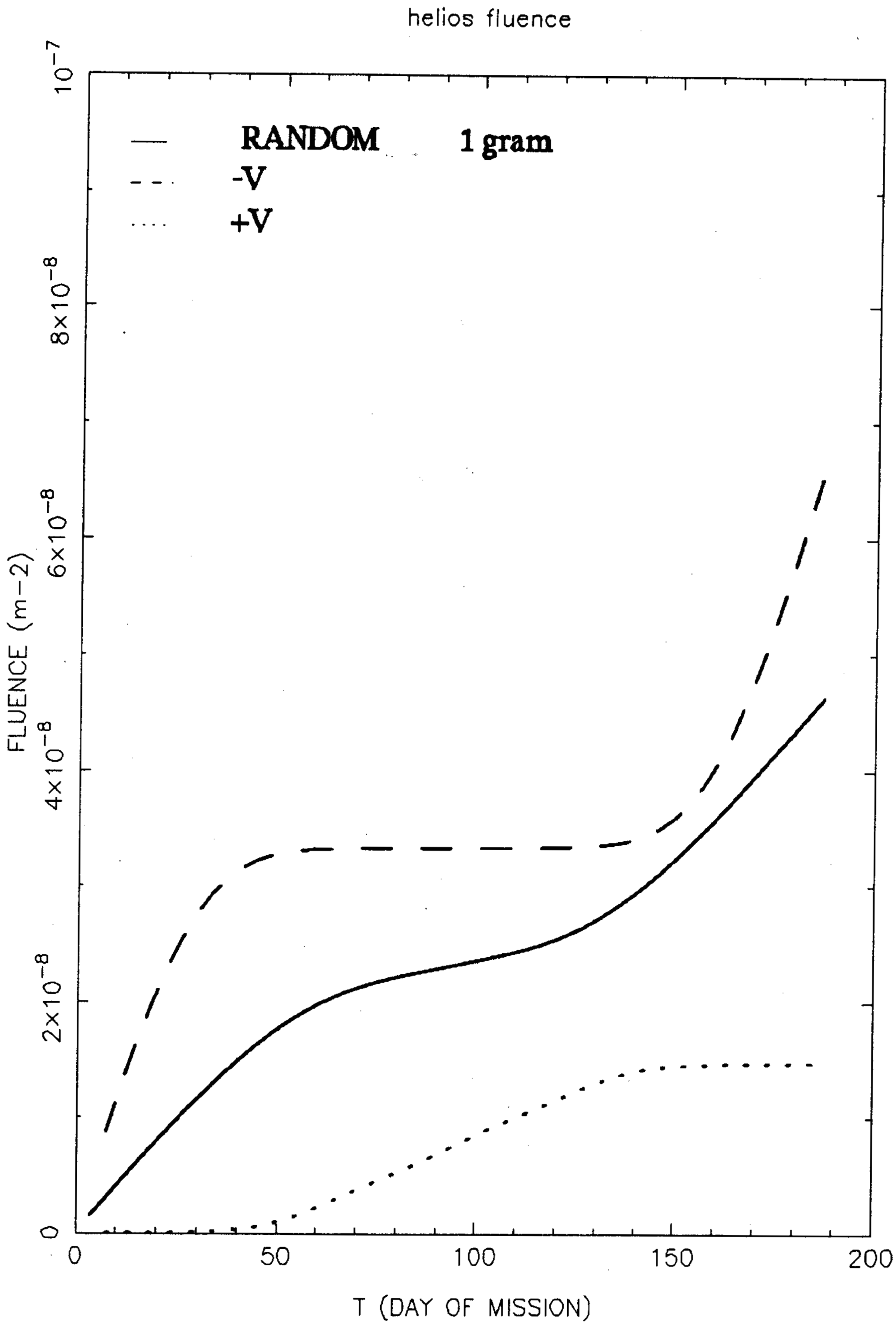

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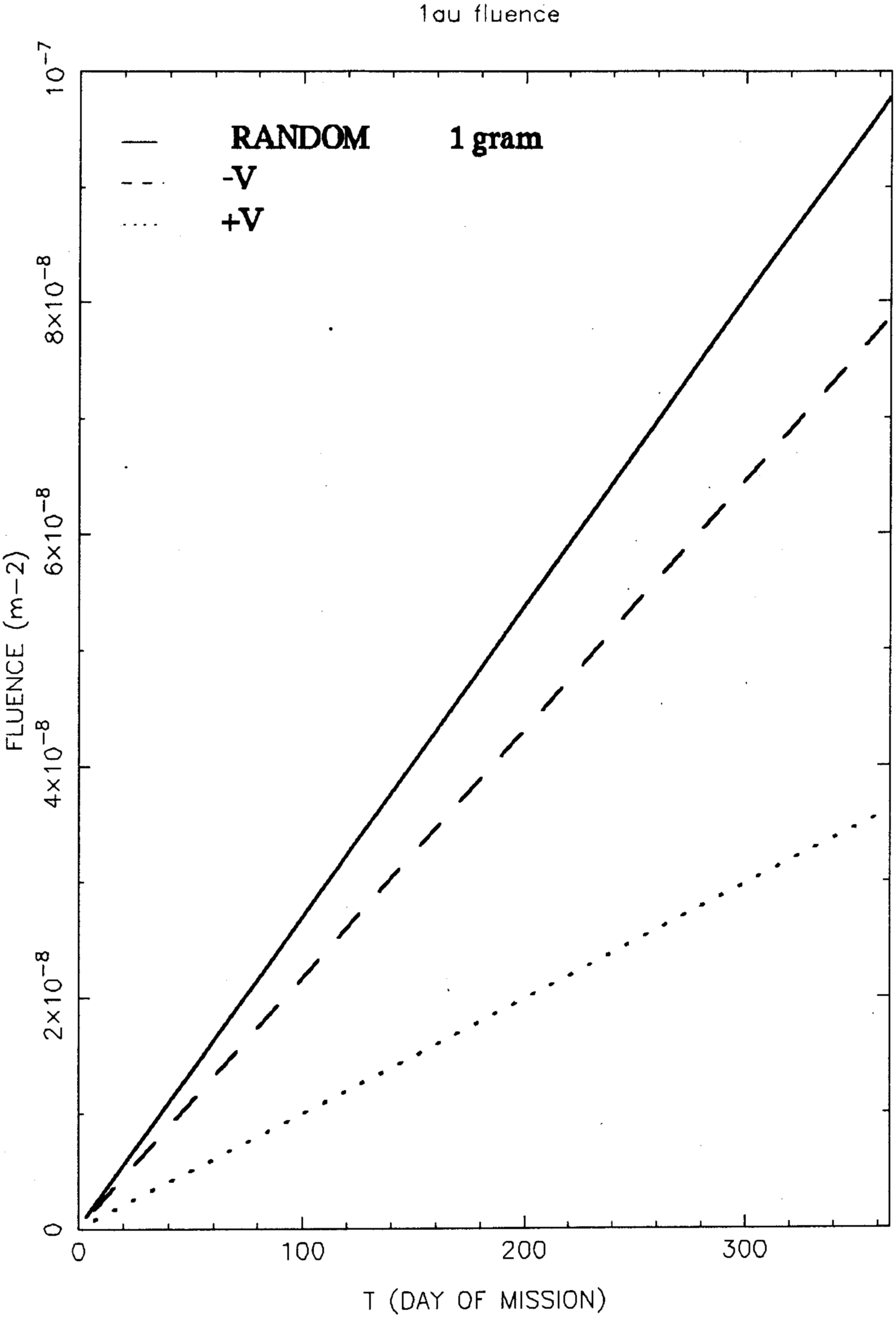

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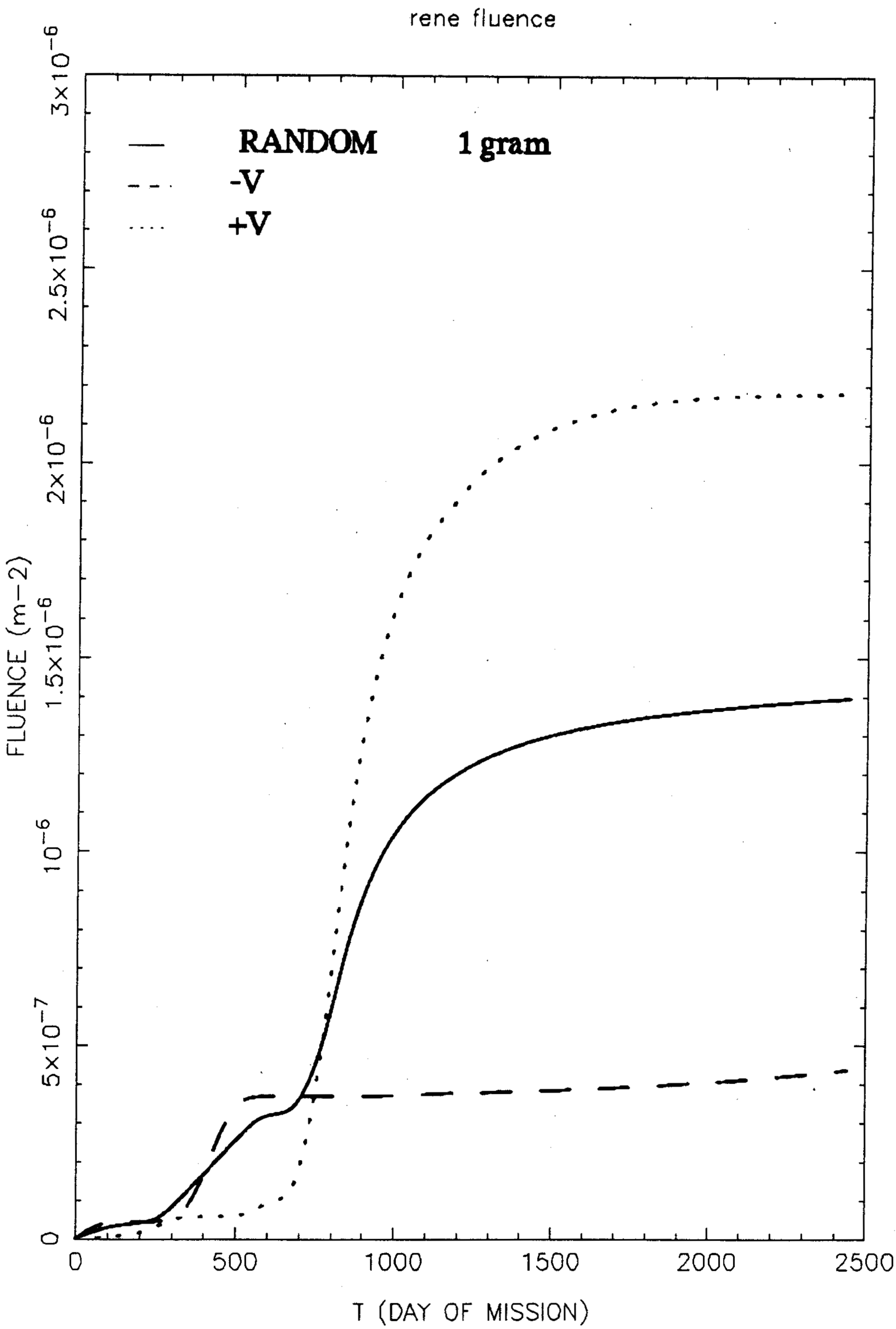

Henry Garrett, Fig. 15